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Measuring the absolute DT neutron yield using the Magnetic Recoil Spectrometer at OMEGA and the NIF

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A Magnetic Recoil Spectrometer (MRS) has been installed and extensively used on OMEGA and the National Ignition Facility (NIF) for measurements of the absolute neutron spectrum from inertial confinement fusion (ICF) implosions. From the neutron spectrum measured with the MRS, many critical implosion parameters are determined including the primary DT neutron yield, the ion temperature, and the down-scattered neutron yield. As the MRS detection efficiency is determined from first principles, the absolute DT neutron yield is obtained without cross-calibration to other techniques. The MRS primary DT neutron measurements at OMEGA and the NIF are shown to be in excellent agreement with previously established yield diagnostics on OMEGA, and with the newly commissioned nuclear activation diagnostics on the NIF.

In Inertial Confinement Fusion (ICF) experiments performed at the OMEGA laser[1] and the National Ignition Facility (NIF),[2] the primary neutron yield is one of the most fundamental parameters that can be measured, as it relates to the number of fusion reactions and fusion energy released. This makes the neutron yield a crucial parameter for diagnosing performance in ICF implosions. Furthermore, the yield will indicate if ignition[3-5] has occurred in experiments currently being conducted at the NIF. Many yield diagnostic techniques[6-9] exist, but the harsh ICF environment makes determining the absolute yield, with high accuracy, very challenging. Hence, multiple measurements conducted with different techniques are essential for establishing the fidelity of the resulting yield data. In particular, the yield from the Magnetic Recoil Spectrometer (MRS) data is determined from first principles,[10-13] without cross-calibration. In this paper, absolute yields obtained with the MRS are compared to other techniques and the results indicate good agreement between the different measurements.

This paper is structured as follows: Section I discusses the diagnostic principle of the MRS. Section II shows the MRS yields at OMEGA and the NIF, and how these compare to other measurements. Section III outlines future work, while Section IV summarizes the paper.

I. MRS Principle

The MRS consists of four main components; a CH_2 (or CD_2) foil positioned at 10 cm and 26 cm from the implosion at OMEGA[1] and the NIF,[2] respectively; a focusing magnet that is located outside the target chamber; and an array of CR-39 nuclear-track detectors positioned at the focal plane of the spectrometer. In addition to these four components, which are shown schematically in Figure 1, the MRS is enclosed by polyethylene shielding to suppress the ambient neutron background.

The MRS principle is as follows: a small fraction of the neutrons emitted from the implosion hit the CH_2 or CD_2 foil, producing scattered recoil protons or deuterons in the forward direction. Some of these forward scattered recoil protons or deuterons are selected by an aperture, positioned in front of the magnet. The selected recoil particles are energy-dispersed by their momentum in the MRS magnetic field and focused onto an array of CR-39 detectors. The measured recoil spectrum is then used to determine the neutron spectrum emitted from the implosion.

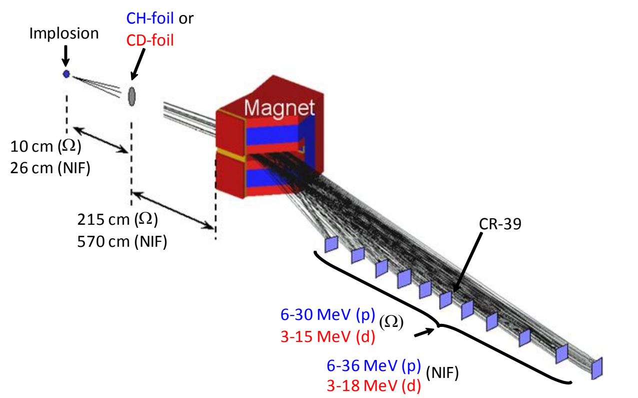

Figure 1: A schematic drawing of the MRS and its three main components: a CH_2 (or CD_2) foil, magnet, and an array of CR-39 detectors. The MRS uses the foil to convert incident neutrons into recoil charged particles. Forward scattered recoil protons or deuterons are selected by an aperture in front of the magnet. Selected recoil particles are momentum analyzed and focused onto an array of CR-39 detectors, which record the position and therefore energy of each recoil particle. The measured recoil spectrum is then used to determine the neutron spectrum from the implosion. The polyethylene neutron shielding that encloses the MRS is not shown.

II. MRS Measurements of the Yield on OMEGA and the NIF

The DT reaction yield (Y_{DT}) is determined from the number of counts (S) in the MRS measured spectrum (in the region corresponding to the Doppler broadened primary neutron spectrum)[14] and detection efficiency of the system (ε_{DT}) (discussed in detail in ref. [15]). If capsule self-attenuation is small and there are no other significant sources of neutrons in the vicinity of the primary spectrum, such as down-scattered neutrons (DSn) produced in high areal density (>0.1g/cm^2) implosions, then the reaction yield can be determined directly using $Y_{DT}=S/\varepsilon_{DT}$.[d)] As the detection efficiency is a function of neutron energy (caused by the energy dependence of the elastic (n,d) scattering cross-section in the foil),[16] a primary-neutron weighted ε_{DT} must be used in the analysis. In high-ρR implosions at the NIF, attenuation[d)] and the resulting DSn spectrum are significant and must be considered. Therefore, the integral over the energy range of 13-15 MeV is used for the determination of the neutron yield (or $Y_{13\text{-}15}$). The energy dependence of ε_{DT} is accounted for through a forward-fit analysis of the measured spectrum using the MRS response function. For high-ρR implosions, the relationship between $Y_{13\text{-}15}$ and the total DT reaction yield requires either measurement of the full neutron spectrum (with models of the various components) or coupled hydrodynamic and neutron transport modeling of attenuation and neutron scattering during the implosion, performed using codes such as LASNEX or HYDRA.[5]

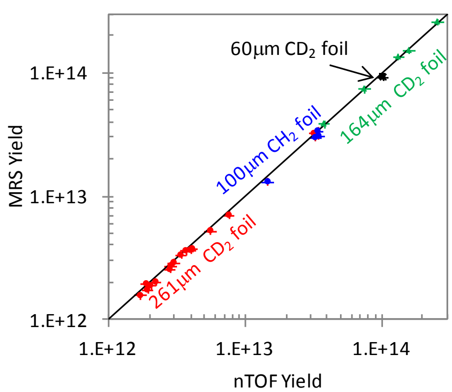

Figure 2: OMEGA MRS primary neutron yield as a function of nTOF primary neutron yield. Excellent agreement between the measurements is observed for a wide range of implosion-yields. Three different CD_2 foils and one CH_2 foil were used for the MRS in these experiments.

At OMEGA, the MRS is complemented by neutron time-of-flight (nTOF) detectors.[6, 7, 17] The systematic uncertainty of the nTOF yield data is 5% at OMEGA,[18,9, 19] while the systematic uncertainty associated with the OMEGA MRS and the NIF MRS yield is 9% and 4.3%, respectively.[20] Figure 2 shows the determined MRS primary yields produced in gas-filled and cryogenic DT implosions, compared to nTOF primary yields, ranging from Y_{DT} ~2×10^{12} - 2×10^{14}. A 100μm thick CH_2 foil and three different CD_2 foils (ranging from 60 to 261μm in thickness) were used for these measurements. Because much of the systematic uncertainties associated with the MRS yield are foil-specific, using multiple foils results in a smaller systematic error of 6% compared to the 9% estimated for a single foil. The data shows excellent agreement between the two measurements over several orders of magnitude. A closer look reveals that the MRS provides a yield that is on average 0.99±0.02 (statistical error only) of the nTOF yield.

A large suite of nuclear diagnostics has been commissioned on the NIF. This includes the MRS, nTOFs,[7] neutron imaging,[21] Zr activation,[19,22] Cu activation,[6, 8] and the Gamma-ray-burn-history (GRH) detector.[23] These diagnostics have been fielded on DT gas-filled exploding-pusher implosions and cryogenically layered DT and THD implosions, producing a wide range of neutron yields. The MRS yield has been compared to the Zr and Cu activation measurements, which are also absolutely calibrated (the NIF nTOF detectors were calibrated with the MRS, Zr activation, and Cu activation data and thus excluded in this comparison).[24] The yields determined from the MRS data, as a function of the activation data, are shown in Figure 3. Here, five different CD_2 foils where used with thickness ranging from 47 to 259μm. Again, the comparison using multiple foils decreases the MRS systematic error to 3.6%. Excellent agreement between the two sets of data is observed. On average, the MRS-to-activation-yield ratio is 0.98±0.02 (for all DT shots from September 2010 to April 12, 2012).

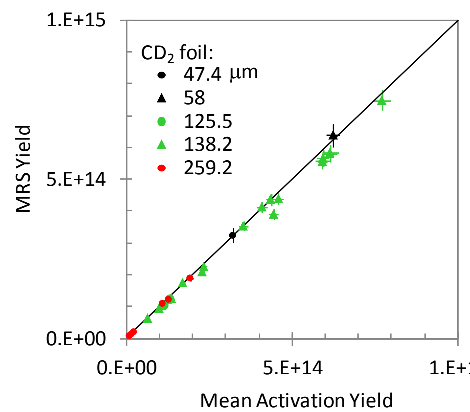

Figure 3: Absolute primary neutron yield (integrated between 13-15 MeV) measured by the NIF MRS as a function of the primary yield measured by Zr and Cu activation (uncertainty weighted mean). Given the absolute uncertainties, excellent agreement between the measurements is observed, providing confidence in the absolute primary yield measured at the NIF.

III. Future work

As the systematic uncertainty typically dominates the statistical uncertainty in the MRS data, better characterization of the different MRS parameters will reduce the uncertainty in the determined primary neutron yield. We are therefore in the process of reducing the dominant sources of the systematic uncertainties. At both OMEGA and the NIF, the uncertainty in the differential cross-section for (n,d) elastic scattering in the foil is important. Faddeev calculations of the (n,d) elastic scattering cross-section, for neutron energies in the range 3-18 MeV, were recently conducted to an accuracy of 1%.[25,26] These cross-sections are planned to replace the cross-sections currently used[16] in the modeling of the MRS-response function, improving the systematic uncertainty in NIF-MRS yield from 4.3% to 3.7%. For the OMEGA MRS, the uncertainty due to geometric and positioning issues (8% of the total error) needs to be considered as well. A redesigned foil holder is expected to improve the systematic uncertainty from 9% to 6%.

IV. Summary

As the MRS detection efficiency is determined from first principles, the absolute primary neutron yield from an ICF implosion is determined directly from the measured data without cross-calibration. The results obtained at OMEGA and the NIF are good agreement with other measurements, clearly demonstrating the high fidelity of the yield data at these facilities. To enhance the capability of the MRS, the systematic uncertainties associated with the MRS yield measurement is actively being reduced.

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V. References

a) This work was done in partial completion of a Ph.D. thesis.
b) Also Visiting Senior Scientist at the Laboratory for Laser Energetics, University of Rochester
c) Also Department of Mechanical Engineering, and Physics and Astronomy, University of Rochester.
d) An estimate of the difference between Y_{DT} and the observed neutron yield can be derived by calculating the approximate number of DT neutrons that scatter. This is ~ 1-EXP(-$\rho R\sigma/m$), or simply ~ 0.2 ρR[g/cm^2] for ρR < 1 g/cm^2. Therefore, the actual reaction yield is higher than the observed yield by ~2% for a 0.1 g/cm^2 implosion.

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